HETEROGENEOUS SHALLOW-SHELF CARBONATE BUILDUPS IN THE PARADOX BASIN, UTAH AND COLORADO: TARGETS FOR INCREASED OIL PRODUCTION AND RESERVES USING HORIZONTAL DRILLING TECHNIQUES

SEMI-ANNUAL TECHNICAL PROGRESS REPORT April 6, 2004 - October 5, 2004

by

Thomas C. Chidsey, Jr., Principal Investigator/Program Manager,
Utah Geological Survey,
and
David E. Eby, Eby Petrography & Consulting, Inc.

UTAH GEOLOGICAL SURVEY

December 2004

Contract No. DE-FC26-00BC15128

Gary D. Walker, Contract Manager
U.S. Department of Energy
National Petroleum Technology Office
1 West 3rd Street
Tulsa, OK 74103-3532

DISCLAIMER

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ABSTRACT

The Paradox Basin of Utah, Colorado, Arizona, and New Mexico contains nearly 100 small oil fields producing from carbonate buildups within the Pennsylvanian (Desmoinesian) Paradox Formation. These fields typically have one to 10 wells with primary production ranging from 700,000 to 2,000,000 barrels (111,300-318,000 m^3) of oil per field and a 15 to 20 percent recovery rate. At least 200 million barrels (31.8 million m^3) of oil will not be recovered from these small fields because of inefficient recovery practices and undrained heterogeneous reservoirs.

Several fields in southeastern Utah and southwestern Colorado are being evaluated as candidates for horizontal drilling and enhanced oil recovery from existing vertical wells based upon geological characterization and reservoir modeling case studies. Geological characterization on a local scale is focused on reservoir heterogeneity, quality, and lateral continuity, as well as possible reservoir compartmentalization, within these fields. This study utilizes representative cores, geophysical logs, and thin sections to characterize and grade each field's potential for drilling horizontal laterals from existing development wells. The results of these studies can be applied to similar fields elsewhere in the Paradox Basin and the Rocky Mountain region, the Michigan and Illinois Basins, and the Midcontinent region.

This report covers research activities for the first half of the fifth project year (April 6 through October 5, 2004). The work included epifluorescence analyses of selected reservoir rocks from Cherokee field, San Juan County, Utah. Epifluorescence petrography makes it possible to clearly identify grain types and shapes, within both limestone and dolomite reservoir intervals in upper Ismay zone thin sections from the Cherokee field cores examined in this study. In particular, identification of peloids, skeletal grain types, and coated grains are easy to see in rocks where these grains have been poorly preserved, partially leached, or completely dolomitized. Epifluorescence petrography clearly and rapidly images pore spaces that cannot otherwise be seen in standard viewing under transmitted polarized lighting. Much of the upper Ismay zone porosity is very heterogeneous and poorly connected as viewed under epifluorescence. The epifluorescence examination helps in seeing the dissolution origin of most types of the microporosity. Without the aid of the epifluorescence view, the amount of visible open pore space would be underestimated in the plane-light image.

Where dolomitization has occurred, epifluorescence petrography often shows the crystal size, shape, and zonation far better than transmitted plane or polarized lighting. This information is often very useful when considering the origin and timing of dolomitization as well as evaluating the quality of the pore system within the dolomite. Epifluorescence also frequently reveals small compartments of good porosity separated from much tighter rocks by sub-horizontal stylolitic seams. Hence, some of the stylolites and wispy seams with concentrations of insoluble residues act as barriers to vertical fluid flow between the porous compartments.

Technology transfer activities consisted of exhibiting a booth display of project materials at the annual national and regional conventions of the American Association of Petroleum Geologists, a public presentation to Grand County government officials, and a publication. Project team members met with the Technical Advisory and Stake Holders Boards to review the project activities, results, and recommendations for future work. The project home page was updated for the Utah Geological Survey Web site.

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EXECUTIVE SUMMARY

The project's primary objective is to enhance domestic petroleum production by demonstration and transfer of horizontal drilling technology in the Paradox Basin of Utah and Colorado. If this project can demonstrate technical and economic feasibility, then the technique can be applied to approximately 100 additional small fields in the Paradox Basin alone, and result in increased recovery of 25 to 50 million barrels (4-8 million m^3) of oil. This project is designed to characterize several shallow-shelf carbonate reservoirs in the Pennsylvanian (Desmoinesian) Paradox Formation, choose the best candidate field(s) for a pilot demonstration project to drill horizontally from existing vertical wells, monitor well performance, and report associated validation activities.

The Utah Geological Survey heads a multidisciplinary team to determine the geological and reservoir characteristics of typical, small, shallow-shelf, carbonate reservoirs in the Paradox Basin. The Paradox Basin technical team consists of the Utah Geological Survey (prime contractor), Colorado Geological Survey (subcontractor), Eby Petrography & Consulting Inc. (subcontractor), and Seeley Oil Company (subcontractor and industry partner). This research is partially funded by the Class II Oil Revisit Program of the U.S. Department of Energy, National Petroleum Technology Office (NPTO) in Tulsa, Oklahoma. This report covers research activities for the first half of the fifth project year (April 6 through October 5, 2004). The work included epifluorescence analyses of selected reservoir rocks from Cherokee field, San Juan County, Utah. From these and other project evaluations, untested or under-produced reservoir compartments and trends can be identified as targets for horizontal drilling. The results of this study can be applied to similar reservoirs in many U.S. basins.

Epifluorescence petrography makes it possible to clearly identify grain types and shapes, within both limestone and dolomite reservoir intervals in upper Ismay zone thin sections from the Cherokee field cores examined in this study. In particular, identification of peloids, skeletal grain types, and coated grains are easy to see in rocks where these grains have been poorly preserved, partially leached, or completely dolomitized. Epifluorescence petrography clearly and rapidly images pore spaces that cannot otherwise be seen in standard viewing under transmitted polarized lighting. In many of the microporous limestones and finely crystalline dolomites, the differences between muddy and calcarenitic fabrics can only be clearly appreciated with fluorescence lighting.

Much of the upper Ismay zone porosity is very heterogeneous and poorly connected as viewed under epifluorescence. The epifluorescence examination helps in seeing the dissolution origin of most types of the microporosity. Transmitted polarized lighting does not image microporosity in carbonate samples very well, even though blue-dyed epoxy can be impregnated into even very small pores. This porosity does not show up very well because the pores are much smaller than the thickness of the thin section, and hence carbonate crystallites on either side of micropores are seen rather than the pores. In addition, opaque bitumen linings prevent light from passing through some of the pores to the observer. Without the aid of the epifluorescence view, the amount of visible open pore space would be underestimated in the plane-light image.

Where dolomitization has occurred, epifluorescence petrography often shows the crystal size, shape, and zonation far better than transmitted plane or polarized lighting. This information is often very useful when considering the origin and timing of dolomitization as well as evaluating the quality of the pore system within the dolomite. Low-permeability

carbonates from this study area show bright yellow fluorescence due to trapped live oil that is retained within tighter parts of the reservoir system. More permeable rocks show red fluorescence due to the epoxy fluorescence where oil has almost complete drained from the better quality portions of the reservoir.

Epifluorescence frequently reveals small compartments of good porosity separated from much tighter rocks by subhorizontal stylolitic seams. Hence, some of the stylolites and wispy seams with concentrations of insoluble residues act as barriers to vertical fluid flow between the porous compartments.

Technology transfer activities for the reporting period consisted of a non-technical presentation to the Grand County Council, members of the press, and general public. The petroleum geology of the Paradox Basin and an overview of project goals, activities, and results were part of the presentation. Project materials, plans, objectives, and results were displayed at the Utah Geological Survey booth during the American Association of Petroleum Geologists (AAPG) Annual Convention, April 18-24, 2004, in Dallas, Texas, and at the AAPG Rocky Mountain Section Meeting/Rocky Mountain Natural Gas Strategy Conference and Investment Forum, August 9-11, 2004, in Denver, Colorado. Project team members also met with the Technical Advisory and Stake Holders Boards to review the project activities, results, and recommendations for future work. The project home page was updated on the Utah Geological Survey Web site. Project team members also published the semi-annual report detailing project progress and results.

INTRODUCTION

Project Overview

Over 400 million barrels (64 million m^3) of oil have been produced from the shallow-shelf carbonate reservoirs in the Pennsylvanian (Desmoinesian) Paradox Formation in the Paradox Basin, Utah and Colorado (figure 1). With the exception of the giant Greater Aneth field, the other 100-plus oil fields in the basin typically contain 2 to 10 million barrels (0.3-1.6 million m^3) of original oil in place. Most of these fields are characterized by high initial production rates followed by a very short productive life (primary), and hence premature abandonment. Only 15 to 25 percent of the original oil in place is recoverable during primary production from conventional vertical wells.

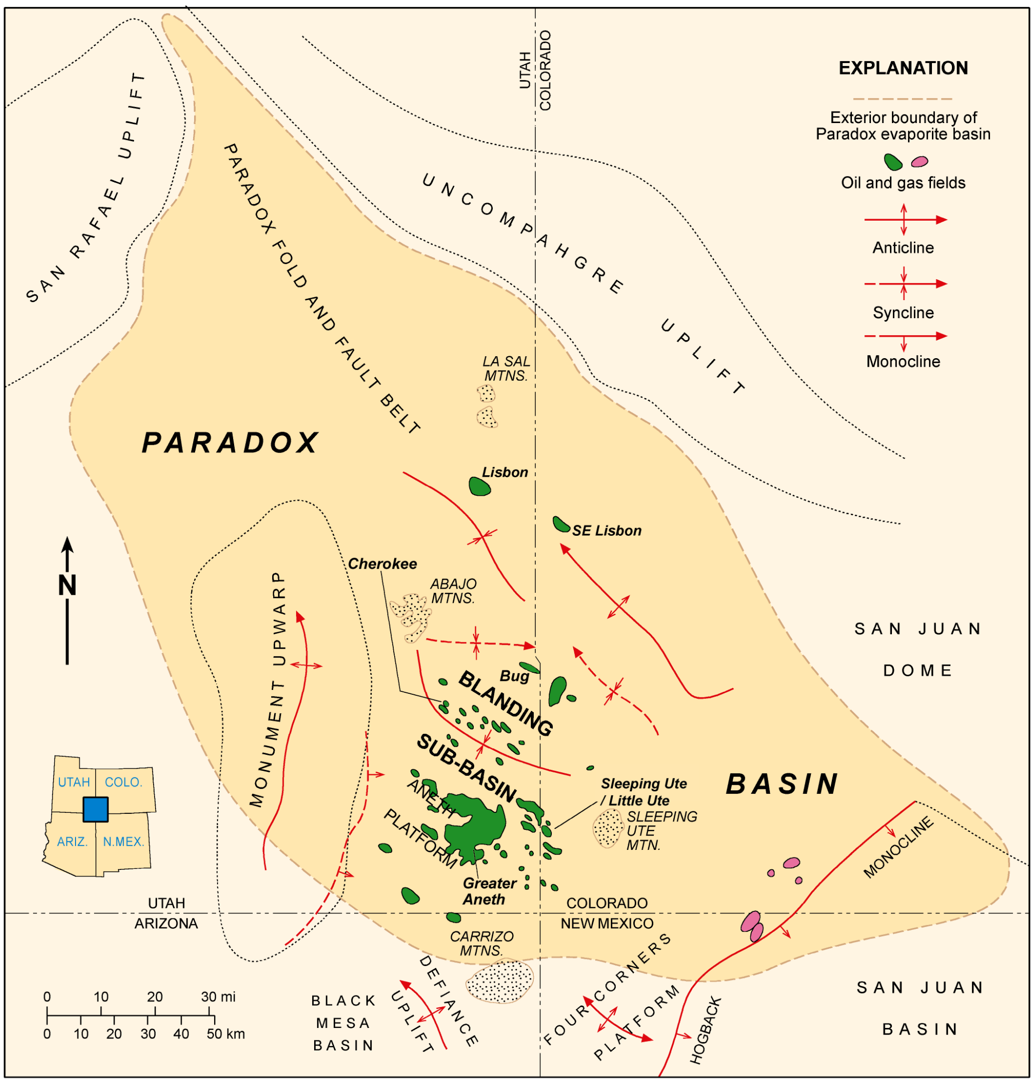


Figure 1. Location map of the Paradox Basin, Utah, Colorado, Arizona, and New Mexico, showing producing oil and gas fields, the Paradox fold and fault belt, and Blanding sub-basin as well as surrounding Laramide basins and uplifts (modified from Harr, 1996).

An extensive and successful horizontal drilling program has been conducted in the giant Greater Aneth field. However, to date, only two horizontal wells have been drilled in small Ismay and Desert Creek fields. The results from these wells were disappointing due to the previously poor understanding of the carbonate facies and diagenetic fabrics that create reservoir heterogeneity. These small fields, and similar fields in the basin, are at high risk of premature abandonment. At least 200 million barrels (31.8 million m^3) of oil will be left behind in these small fields because current development practices leave compartments of the heterogeneous reservoirs undrained. Through proper geological evaluation of the reservoirs, production may be increased by 20 to 50 percent through the drilling of low-cost, single, or multilateral horizontal legs from existing vertical development wells. In addition, horizontal drilling from existing wells minimizes surface disturbances and costs for field development, particularly in the environmentally sensitive areas of southeastern Utah and southwestern Colorado.

The Utah Geological Survey (UGS), Colorado Geological Survey (CGS), Eby Petrography & Consulting, Inc., and Seeley Oil Company have entered into a cooperative agreement with the U.S. Department of Energy (DOE) as part of its Class II Oil Revisit Program. A three-phase, multidisciplinary approach is planned to increase production and reserves from the shallow-shelf carbonate reservoirs in the Ismay and Desert Creek zones of the Paradox Basin.

Phase 1 is a geological and reservoir characterization of selected, diversified, small fields, including Cherokee and Bug fields in San Juan County, Utah (figure 1), to identify those field(s) having the greatest potential as targets for increased well productivity and ultimate recovery in a pilot demonstration project. This phase includes: (a) determination of regional geological setting; (b) analysis of the reservoir heterogeneity, quality, lateral continuity, and compartmentalization within the fields; (c) construction of lithologic, microfacies, porosity, permeability, and net pay maps of the fields; (d) determination of field reserves and recovery; and (e) integration of geological data in the design of single or multiple horizontal laterals from existing vertical wells.

Phase 2 is a field demonstration project of the horizontal drilling techniques identified as having the greatest potential for increased field productivity and ultimate recovery. The demonstration project will involve drilling one or more horizontal laterals from the existing, vertical, field well(s) to maximize production from the zones of greatest potential.

Phase 3 includes: (a) reservoir management and production monitoring, (b) economic evaluation of the results, and (c) determination of the ability to transfer project technologies to other similar fields in the Paradox Basin and throughout the U.S.

Phases 1, 2, and 3 will have continuous, but separate, technical transfer activities including: (a) an industry outreach program; (b) a core workshop/seminar in Salt Lake City; (c) publications and technical presentations; (d) a project home page on the Utah Geological Survey and Colorado Geological Survey Web sites; (e) digital databases, maps, and reports; (f) a summary of regulatory, economic, and financial needs; and (g) annual meetings with a Technical Advisory Board and Stake Holders Board.

This report covers research activities for the first half of the fifth project year (April 6 through October 5, 2004). The work included epifluorescence analyses of selected reservoir rocks from Cherokee field, San Juan County, Utah.

Project Benefits and Potential Application

The overall benefit of this multi-year project would be enhanced domestic petroleum production by demonstrating and transferring an advanced-oil-recovery technology throughout the small oil fields of the Paradox Basin. Specifically, the benefits expected from the project are: (1) increasing recovery and reserve base by identifying untapped compartments created by reservoir heterogeneity; (2) preventing premature abandonment of numerous small fields; (3) increasing deliverability by horizontally drilling along the reservoir's optimal fluid-flow paths; (4) identifying reservoir trends for field extension drilling and stimulating exploration in Paradox Basin fairways; (5) reducing development costs by more closely delineating minimum field size and other parameters necessary for horizontal drilling; (6) allowing for minimal surface disturbance by drilling from existing, vertical, field well pads; (7) allowing limited energy investment dollars to be used more productively; and (8) increasing royalty income to the federal, state, and local governments, the Ute Mountain Ute Indian Tribe, and fee owners. These benefits may also apply to other areas, including algal-mound and carbonate buildup reservoirs on the eastern and northwestern shelves of the Permian Basin in Texas, Silurian pinnacle and patch reefs of the Michigan and Illinois Basins, and shoaling carbonate island trends of the Williston Basin.

The results of this project are transferred to industry and other researchers through Technical Advisory and Stake Holders Boards, an industry outreach program, digital project databases, and project Web pages. Project results are also disseminated via technical workshops and seminars, field trips, technical presentations at national and regional professional meetings, and papers in various technical or trade journals.

GEOLOGIC SETTING

The Paradox Basin is located mainly in southeastern Utah and southwestern Colorado with small portions in northeastern Arizona and the northwestern corner of New Mexico (figure 1). The Paradox Basin is an elongate, northwest-southeast-trending, evaporitic basin that predominately developed during the Pennsylvanian (Desmoinesian), about 330 to 310 million years ago (Ma). During the Pennsylvanian, a pattern of basins and fault-bounded uplifts developed from Utah to Oklahoma as a result of the collision of South America, Africa, and southeastern North America (Kluth and Coney, 1981; Kluth, 1986), or from a smaller scale collision of a microcontinent with south-central North America (Harry and Mickus, 1998). One result of this tectonic event was the uplift of the Ancestral Rockies in the western United States. The Uncompahgre Highlands in eastern Utah and western Colorado initially formed as the westernmost range of the Ancestral Rockies during this ancient mountain-building period. The Uncompahgre Highlands (uplift) is bounded along the southwestern flank by a large basement-involved, high-angle, reverse fault identified from geophysical seismic surveys and exploration drilling. As the highlands rose, an accompanying depression, or foreland basin, formed to the southwest — the Paradox Basin. Rapid subsidence, particularly during the Pennsylvanian and then continuing into the Permian, accommodated large volumes of evaporitic and marine sediments that intertongue with non-marine arkosic material shed from the highland area to the northeast (Hintze, 1993). The Paradox Basin is surrounded by other uplifts and basins that formed during the Late Cretaceous-early Tertiary Laramide orogeny (figure 1).

The Paradox Basin can generally be divided into two areas: the Paradox fold and fault belt in the north, and the Blanding sub-basin in the south-southwest (figure 1). Most oil production comes from the Blanding sub-basin. The source of the oil is several black, organic-rich shales within the Paradox Formation (Hite and others, 1984; Nuccio and Condon, 1996). The relatively undeformed Blanding sub-basin developed on a shallow-marine shelf which locally contained algal-mound and other carbonate buildups in a subtropical climate.

The two main producing zones of the Paradox Formation are informally named the Ismay and the Desert Creek (figure 2). The Ismay zone is dominantly limestone, comprising equant buildups of phylloid-algal material with locally variable, small-scale subfacies (figure 3A) and capped by anhydrite. The Ismay produces oil from fields in the southern Blanding sub-basin (figure 4). The Desert Creek zone is dominantly dolomite, comprising regional, nearshore, shoreline trends with highly aligned, linear facies tracts (figure 3B). The Desert Creek produces oil in fields in the central Blanding sub-basin (figure 4). Both the Ismay and Desert Creek buildups generally trend northwest-southeast. Various facies changes and extensive diagenesis have created complex reservoir heterogeneity within these two diverse zones.

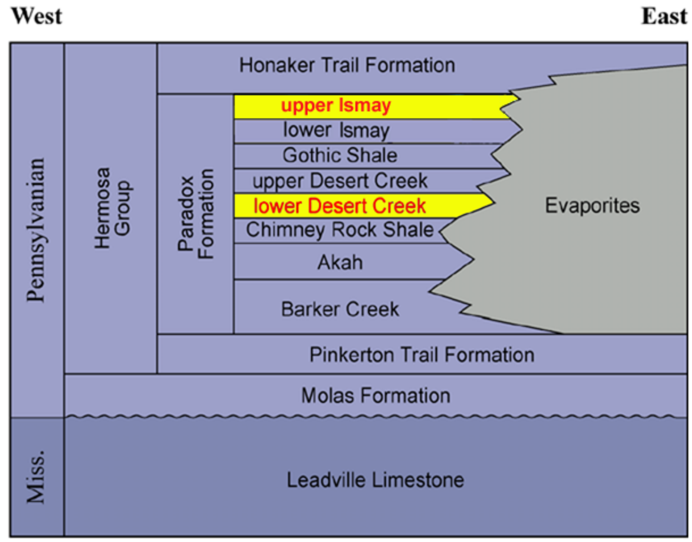


Figure 2. Pennsylvanian stratigraphy of the southern Paradox Basin including informal zones of the Paradox Formation.

CHEROKEE FIELD, SAN JUAN COUNTY, UTAH

Cherokee field in the Ismay trend of San Juan County, Utah was selected for local-scale evaluation and geological characterization (figure 4). The diagenetic evaluation included blue-light epifluorescence microscopy of selected samples from wells in the field, summarized in this report.

The geological characterization focused on reservoir heterogeneity, quality, and lateral continuity, as well as possible compartmentalization within the field. From these evaluations, untested or under-produced compartments are being identified as targets for horizontal drilling. The models resulting from the geological and reservoir characterization of these fields can be applied to similar fields in the basin (and other basins as well) where data might be limited. Modification of rock fabrics and porosity within the lower Desert Creek and upper Ismay zones of the Blanding sub-basin study area is quite complex. Diagenesis played a major role in the development of reservoir heterogeneity in Cherokee field as well as throughout the all of the Paradox Formation fields. Diagenetic processes started during deposition and continued throughout burial history. A complete discussion on the diagenetic history based upon visual core examination and thin section petrography is contained in separate deliverables already completed for this project.

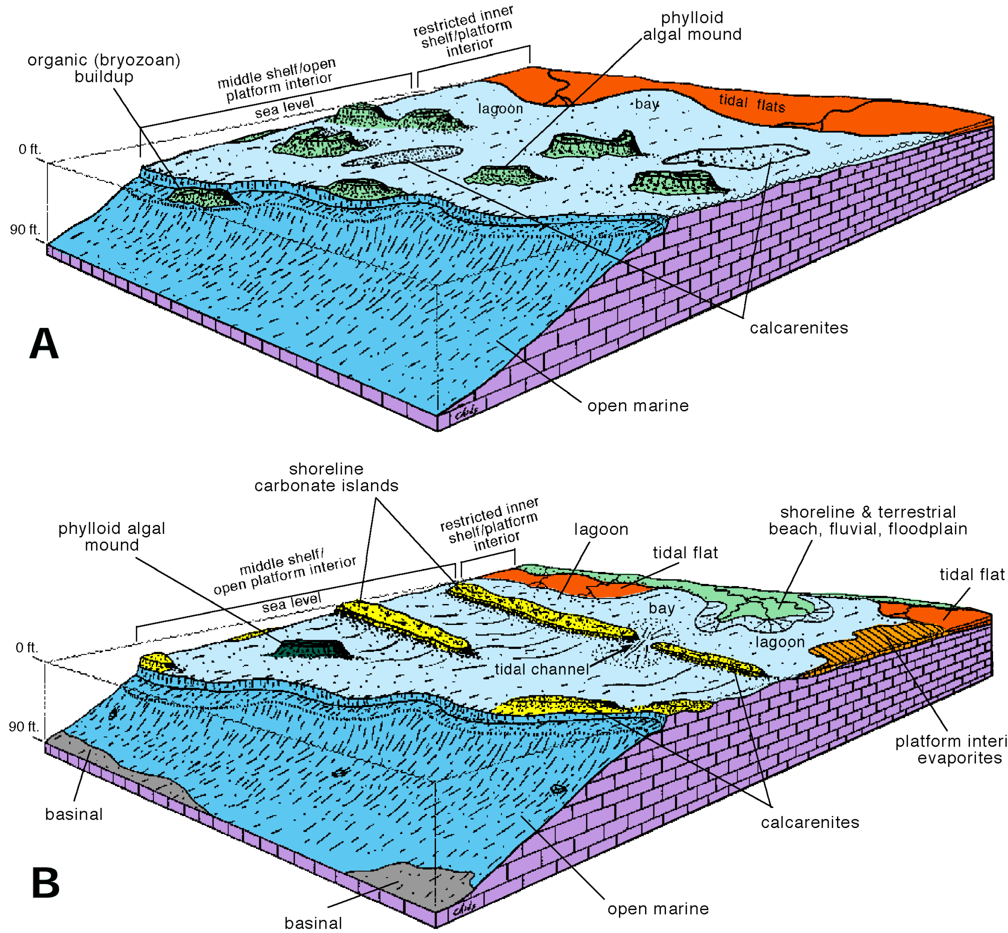


Figure 3. Block diagrams displaying major depositional facies, as determined from core, for the Ismay (A) and Desert Creek (B) zones, Pennsylvanian Paradox Formation, Utah and Colorado.

Cherokee field (figure 4) is a phylloid-algal buildup capped by anhydrite that produces from porous algal limestone and dolomite in the upper Ismay zone. The net reservoir thickness is 27 feet (8.2 m), which extends over a 320-acre (130 ha) area. Porosity averages 12 percent with 8 millidarcies (mD) of permeability in vuggy and intercrystalline pore systems. Water saturation is 38.1 percent (Crawley-Stewart and Riley, 1993).

Cherokee field was discovered in 1987 with the completion of the Meridian Oil Company Cherokee Federal 11-14, NE1/4NW1/4 section 14, T. 37 S., R. 23 E., Salt Lake Base Line and Meridian (SLBL&M); initial flowing potential (IFP) was 53 barrels of oil per day (BOPD) (8.4 m^3), 990 thousand cubic feet of gas per day (MCFGPD) (28 MCMPD), and 26 barrels of water (4.1 m^3). There are currently four producing (or shut-in) wells and two dry holes in the field. The well spacing is 80 acres (32 ha). The present field reservoir pressure is estimated at 150 pounds per square inch (psi) (1034 kPa). Cumulative production as of August 1, 2004, was 182,795 barrels of oil (29,064 m^3), 3.68 billion cubic feet of gas (BCFG) (0.1 BCMG), and 3358 barrels of water (534 m^3) (Utah Division of Oil, Gas and Mining, 2004). The original estimated primary recovery is 172,000 barrels of oil (27,348 m^3) and 3.28 BCFG (0.09 BCMG) (Crawley-Stewart and Riley, 1993). The fact that both these estimates have been surpassed suggests significant additional reserves could remain.

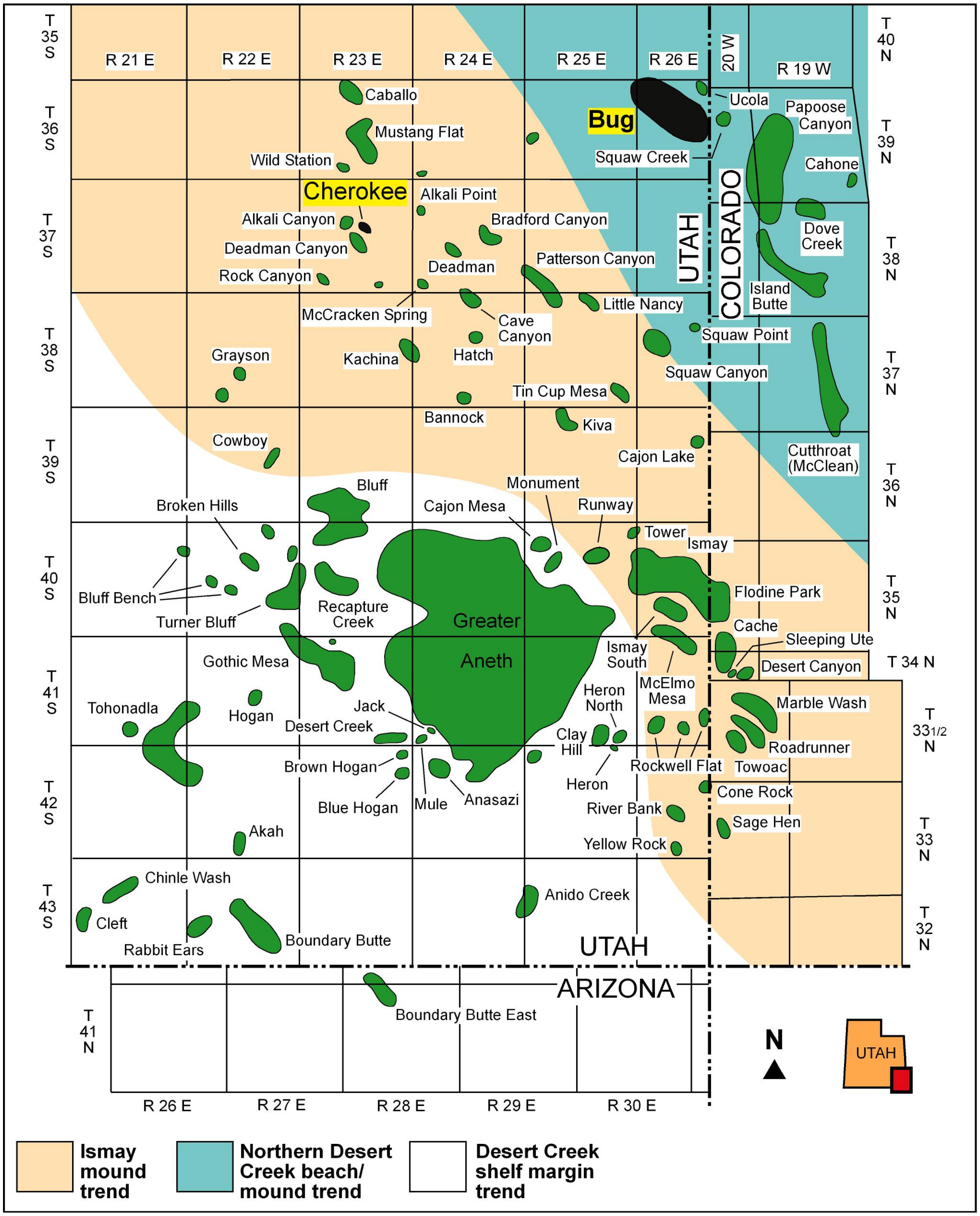


Figure 4. Project study area and fields (case-study fields in black) within the Ismay and Desert Creek producing trends in the Blanding sub-basin, Utah and Colorado.

EPIFLUORESCENCE

Epifluorescence microscopy is a technique that has been used successfully in recent years to provide additional information on diagenesis, pores, and organic matter (including "live" hydrocarbons) within sedimentary rocks. It is a rapid, non-destructive procedure that can be done using a high-quality petrographic (polarizing) microscope equipped with reflected light capabilities. The basic principles and equipment for epifluorescence were largely developed in the 1960s and 1970s for applications in coal petrology and palynology (see reviews by van Gijzel, 1967; Teichmuller and Wolf, 1977). All applications depend upon the emission of light (by a material capable of producing fluorescence) that continues only during absorption of the excitation-generating light beam (Rost, 1992; Scholle and Ulmer-Scholle, 2003).

Epifluorescence techniques have been used within industry and research for three objectives. Firstly, epifluorescence microscopy has been used extensively for enhancing petrographic observations, including the recognition of depositional and diagenetic fabrics within recrystallized limestone and massive dolomite (see, for instance, Dravis and Yurowicz, 1985; Cercone and Pedone, 1987; Dravis, 1991; LaFlamme, 1992). Secondly, the study of pore structures, microfractures, and microporosity within both carbonates and sandstones has been greatly facilitated by impregnating these voids with epoxy spiked with fluorescing dyes (Yanguas and Dravis, 1985; Gies, 1987; Cather and others, 1989a, 1989b; Soeder, 1990; and Dravis, 1991). Thirdly, the evaluation of "oil shows" (Eby and Hager, 1986; Kirby and Tinker, 1992) and determination of the gravity or type cements and minerals has been facilitated by epifluorescence microscopy (Burruss, 1981, 1991; Burruss and others, 1986; Guihaumou and others, 1990; Lavoie and others, 2001). Only the first two objectives were pursued in this study. Also, fluid inclusions were not evaluated in this project.

Previous Work

There is no known published use of epifluorescence microscopy on the upper Ismay and lower Desert Creek subsurface rocks of the Blanding sub-basin. However, the published work cited above, applications to carbonate reservoirs listed in Eby and Hager (1986) for a study done within a Permian Basin carbonate field, and case studies documented by Dravis (1988, 1992) provided incentives to apply epifluorescence petrography to Paradox Formation reservoir rocks within the Cherokee case-study field.

Methodology

Epifluorescence petrography for this project used incident (reflected) blue light fluorescence microscopy employing the general procedures outlined by Dravis and Yurewicz (1985), including the use of the modified "white card" technique outlined by Folk (1987) and Dravis (1991). Ultraviolet (UV) fluorescence did not effectively add any textural or pore structure information that could not otherwise be seen under blue-light excitation, even though some workers utilize UV fluorescence for evaluating fluid inclusions and compositional zoning within dolomite crystals (see Scholle and Ulmer-Scholle, 2003). Fluorescence data and observations collected for this study utilized a Jena (now part of Carl Zeiss) research-grade combination polarizing-reflected light microscope equipped with a high-pressure mercury vapor lamp for epifluorescence excitation, a Zeiss IIIRS epifluorescence nosepiece, and a 35-mm camera system. Magnification ranges for examination and photo-documentation were between ~130 and 320x. The epifluorescence optical configuration used is similar to that shown in figure 5.

The light pathways and mechanics of the epifluorescence used in this study have been generally described by Soeder (1990). As described by Burruss (1991), "these excitation wavelengths are reflected to the microscope objective and sample by a dichroic beamsplitter which has a dielectric coating that reflects a specific short wavelength range. Fluorescence emission and reflected short wavelength excitation light is collected by the objective. The dichroic beamsplitter transmits the long wavelength fluorescence emission, but reflects the short wavelengths back toward the light source. The fluorescence emission passes through a barrier filter which removes any remaining short wavelength excitation light." Blue light (~420-490 nm exciter filter/520 nm barrier filter) was used to excite the cuttings and core-chip samples. We have found broad-band, blue-light epifluorescence to be the most helpful in observational work on dolomite, although some workers report applications using UV light (330-380 nm exciter filter/420 nm barrier filter) or narrow-band, blue-violet light (400-440 nm exciter filter/480 nm barrier filter). Finally, the greater depth of investigation into a sample by the reflected fluorescence technique than by transmitted polarized light or other forms of reflected light make it possible to resolve grain boundary and compositional features that are normally not appreciated in cutting or thin-section petrography.

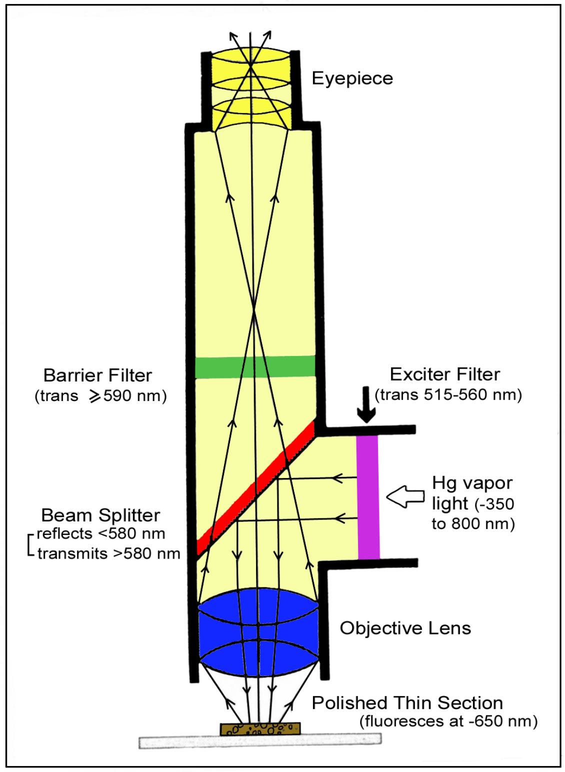


Figure 5. Generalized microscope optical configuration for observing fluorescence under incident light (modified from Soeder, 1990).

Sample preparation is inexpensive and rapid, involving standard thin section preparation techniques. Thin sections were prepared from representative upper Ismay fabrics. These thin sections were vacuum- and pressure-impregnated with blue-dyed epoxy (see Gardner, 1980) that was spiked with a fluorescing compound. Microscopy used only uncovered polished surfaces. Examination for each thin section area of interest included photo-documentation under epifluorescence and plane-polarized light at the same magnification. Photomicrography of the compositional, textural, and pore structure attributes was done using high-speed film (ISO 800 and 1600) with some bracketing of exposures as camera metering systems do not always reliably read these high-contrast images in the yellow and green light spectrum. Since the image brightness is directly proportional to magnification, the best images are obtained at relatively high magnifications (such as greater than 100x). Low-power fluorescence is often too dim to effectively record on film. These techniques are applicable to thin sections from both core and cuttings samples.

Epifluorescence Petrography of Upper Ismay Thin Sections

Blue-light, epifluorescence microscopy was completed on eight core samples for a variety of rock textures and diagenetic phases from upper Ismay zone limestone and dolomite within Cherokee field (figure 4). These samples were selected to be representative of compositional, diagenetic, and pore types encountered within the two cored wells (Cherokee Federal No. 22-14 and Cherokee Federal No. 33-14). A detailed description and interpretation of the fluorescence petrography of each sample follows below along with photomicrographs (as figures 6 through 11) to show representative views under both blue-light epifluorescence and plane-polarized light. Short descriptive captions for these photomicrographs are included with each photo pair.

Cherokee Federal No. 22-14 Well

5768.7 feet: Blue-light, epifluorescence microscopy nicely shows pore spaces and structures that are not readily seen under transmitted, plane-polarized lighting. Black bitumen linings and interlocking, dolomite, crystalline aggregates mask clear definition of the blue-dyed epoxy that has been impregnated into the open pore spaces. However, the reddish fluorescence of the epoxy makes it possible to image pores in cross section very nicely (figure 6). Despite the significant amount of open porosity visible under epifluorescence, many of these voids appear to be completely surrounded by a micro-box-work of dolomite crystals. Much of the dolomite has a dull- to bright-yellow fluorescence, due in part to the presence of live-oil films around many of the tight intercrystalline spaces. There are no identifiable remnants of the original depositional fabric of this carbonate sediment, although the appearance of probable micro-moldic and slightly larger dissolution pores (figure 6) suggests that there were original detrital carbonate grains present.

5778.1 feet: Blue-light, epifluorescence microscopy assists with the identification of fossil fragments and peloids that populate this massive, partially dolomitized limestone. Under plane polarized lighting, this interval appears dense and muddy. However, the fluorescence petrography reveals depositional textures that range from a fine grainstone to packstone (figure 7). In addition, the distribution and types of pores are difficult to identify without examination under fluorescence. Abundant open micropores with some bitumen linings are much easier to see under epifluorescence microscopy than trying to resolve the blue-dyed epoxy that has been impregnated into the sample.

5783.5 feet: This sample displays considerable heterogeneity of porosity and permeability. The epifluorescence petrography nicely shows the location and distribution of pores in cross sections and provides good visual discrimination boundaries (figure 8). Areas of low porosity and permeability show up particularly well because fluorescent live oil is trapped in the tighter (low-permeability) portions of this sample. In addition, this sample displays some relatively large dolomite crystals (>100 µm across) that have replaced the finer carbonate matrix. Where anhydrite has secondarily plugged earlier intercrystalline pores, the differences in fluorescence between oil-impregated dolomite and very massive anhydrite cement are easy to see. Without epifluorescence, the size variation of dolomite crystals and some of the related intercrystalline pore space would be nearly impossible to resolve.

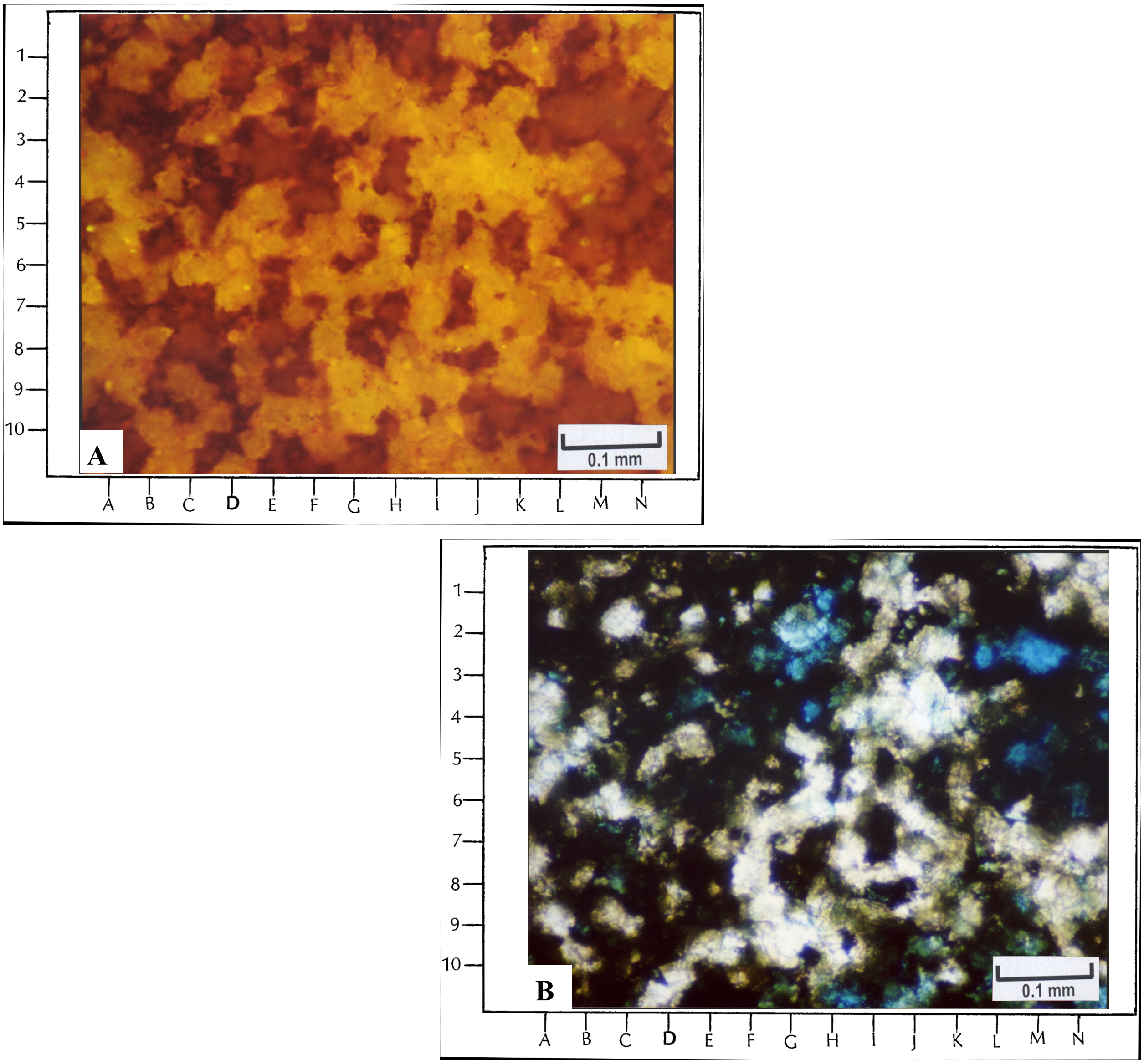
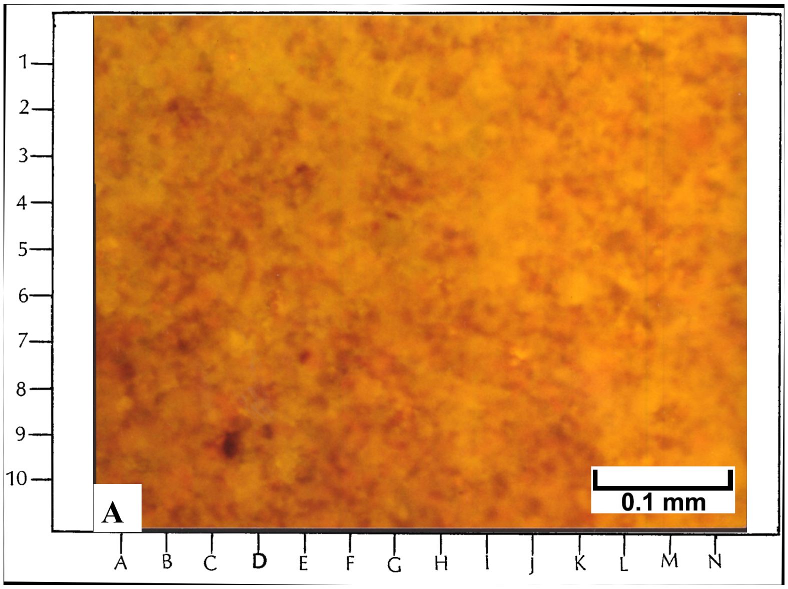


Figure 6. Photomicrographs from Cherokee No. 22-14 well at 5768.7 feet. A - Epifluorescence under moderate magnification of a representative area of microporosity shows outlines of small dolomite crystals (fluorescing yellow here due to oil staining). The reddish areas are pores with abundant bitumen linings and plugging (see figure 6B). Fluorescence petrography makes it possible to clearly see the dolomite crystals versus the pore space. In places, very small rhombic outlines of dolomite crystals can be resolved (see, for instance, E-9, G-4 and N-1). Most of the pores appear in cross section to be poorly size-sorted and of dissolution origin. Many of these pores appear to be completely surrounded by an interlocking network of dolomite crystals (see, for instance, H-3, H-6.5, and J-4). B - The same field of view as above is shown under plane light at the same magnification. Note that the black (and opaque) areas composed of bitumen mask the crystal boundaries of the dolomite as well as individual pore outlines. The white and gray areas are remnants of the dolomite matrix that are not masked by the bitumen. Only a small amount of pore space (blue-dyed areas) can be seen in this view compared to the fluorescence photomicrograph above.



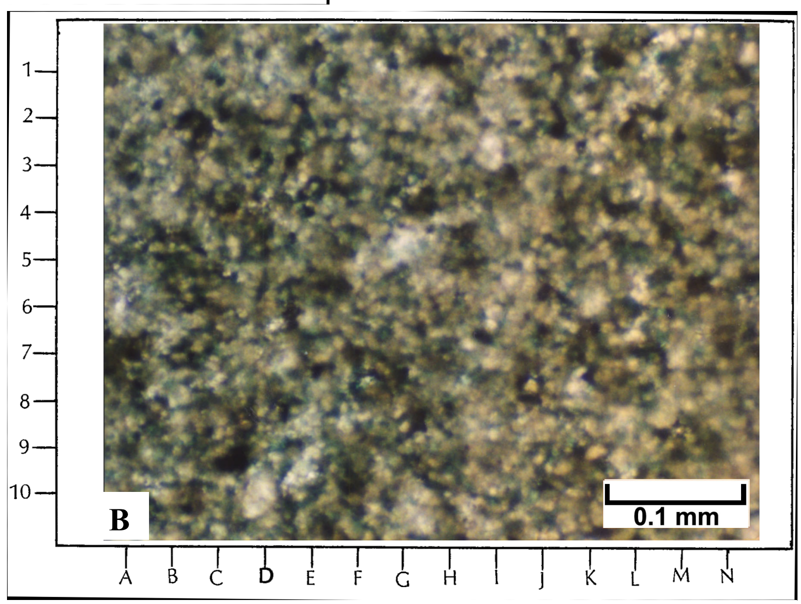


Figure 7. Photomicrographs from Cherokee No. 22-14 well at 5778.1 feet. A - A representative epifluorescence photomicrograph of a dense dolomitic limestone under moderate magnification distinguishes porosity from oil-stained matrix. The reddish areas represent the epoxy-impregnated pores within this sample. The yellow areas are the oil-stained, carbonate, mineral matrix. Note that the fluorescence image helps to identify occult carbonate grains such as probable fossils (for example G-2, H-2, and J-9) and small peloids (for example C-1, I-5, K-8, and so forth) that are not visible in the plane light image. This dense limestone was deposited as a bioclastic-peloidal grainstone to packstone. B - The same field of view as above is shown under plane light at the same magnification. This portion of the sample has been artificially stained with Alizarin Red-S solution. The pink areas are calcite while the white and gray areas are mostly dolomite. The indistinct black patches are indicative of some bitumen plugging within microporous spaces. The bluish areas within this view are due to the impregnation of blue-dyed epoxy into the micropores. However, it is impossible to see any of the carbonate components, the depositional texture, or the open pores without use of epifluorescence lighting as shown above.

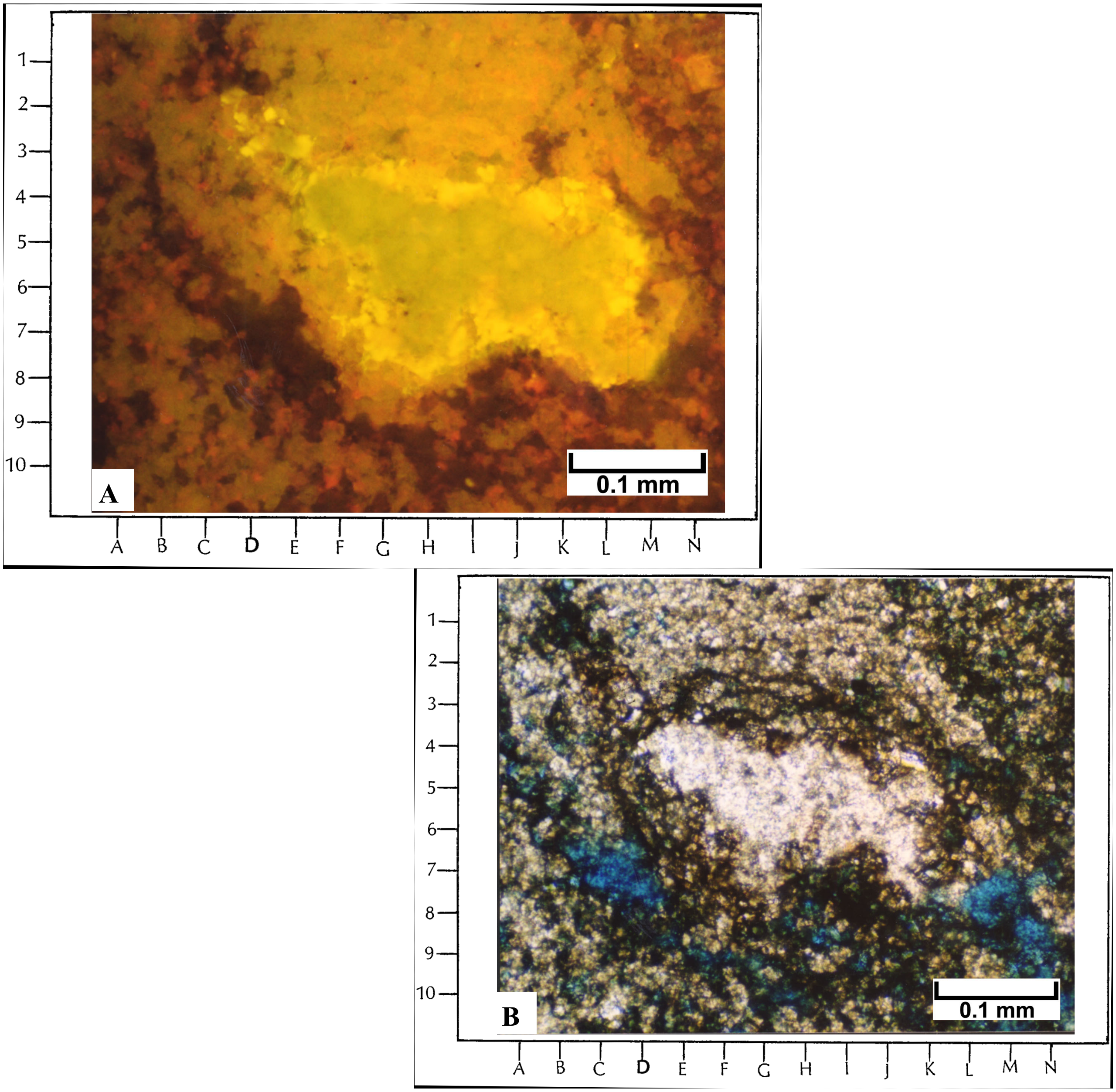


Figure 8. Photomicrographs from Cherokee No. 22-14 well at 5783.5 feet. A - A wide range of information can be seen in this epifluorescence image. The amoeboid, greenish-yellow feature in the center (from F-4 to M-7) is a small nodule of anhydrite surrounded by finely crystalline dolomite. The bright-yellow rim around the anhydrite is due to live oil bleeding out of the dolomite and trapped against the impervious nodule. The dull-yellow areas throughout the remainder of this image consist of dolomite containing small amounts of fluorescing oils. The solid patch of dull fluorescence across the top of this photomicrograph (from E-2 to K-2) is a tight area with interlocking dolomite crystals. The black and dark red areas show where the open pore spaces occur, including pores with some bitumen coatings. Finally, the orangish areas are mostly likely weakly fluorescing portions of bitumen. B - The same field of view as above is shown under plane light at the same magnification. Even though it is possible to identify the white nodule of anhydrite in the center of this field of view, the details of pore distribution, as well as the fluorescence of live oils and bitumen distribution, are not easy to see in this transmitted-light image.

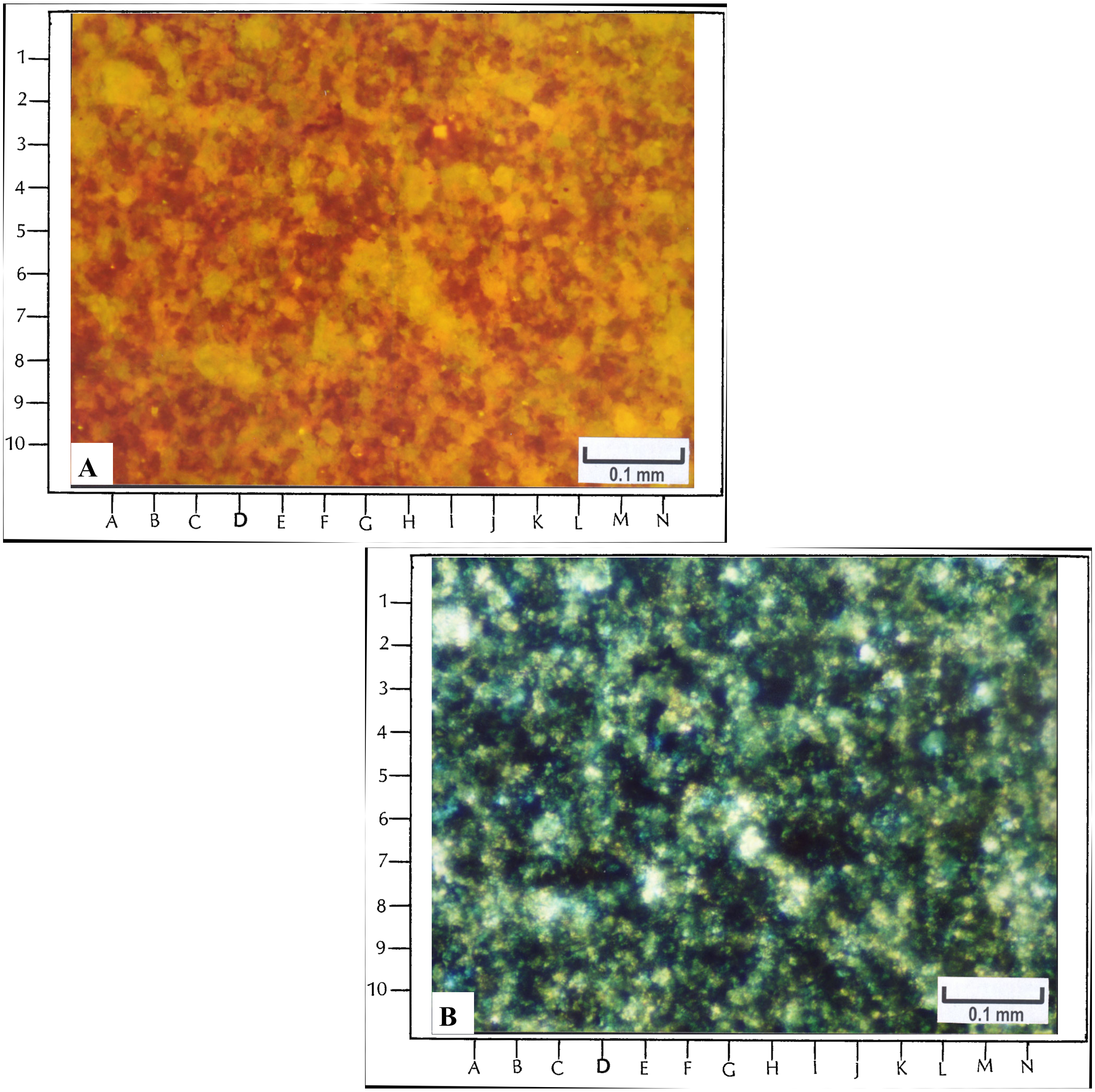


Figure 9. Photomicrographs from Cherokee No. 22-14 well at 5801.3 feet. A - Abundant pore space can be seen in this fluorescence image, where the epoxy-impregnated pores appear red. Despite the heterogeneity of the distribution of pores, most of this microporosity seems to be moderately well connected. The greenish-yellow and yellow colors in this image are from matrix areas composed of dolomite and limestone. The brightest yellow areas reflect staining of the matrix by live oil. Note the hints of earlier sand-sized carbonate grains (for example F-1.5, H-2, and L-5) and occasional, isolated, larger, dolomite rhombs (for example B-1.5, G-7, and K-2). B - The same field of view as above is shown under plane light at the same magnification. Note that the details of the pore sizes and shapes cannot be seen in this transmitted light photo. Abundant black bitumen throughout this microporous network makes it nearly impossible to see the amount of visible porosity. At best, the microporosity in this image shows up as an indistinct "blue haze." In addition, it is not possible to see any hints of original grains or the sizes of dolomite crystals.

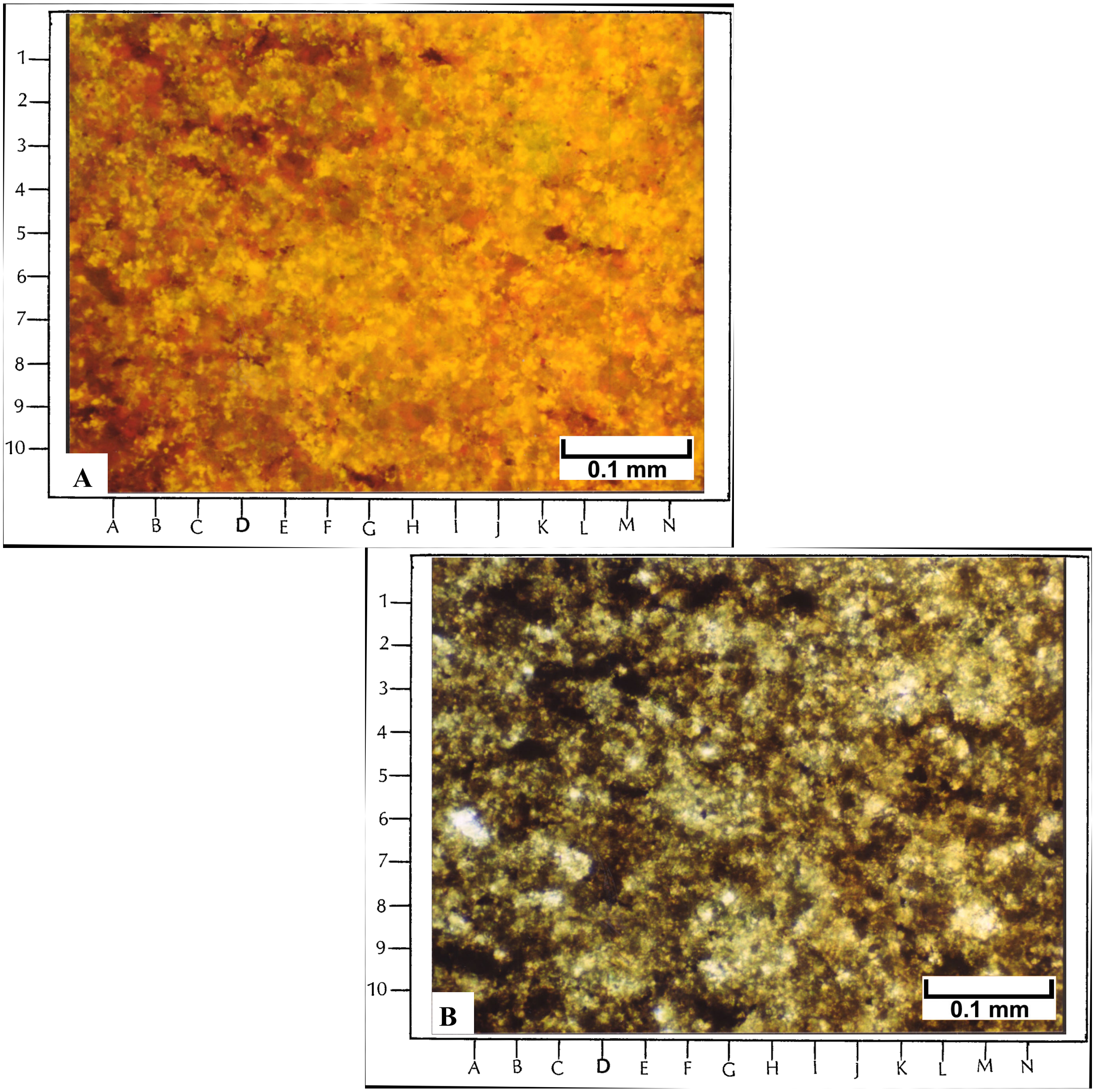


Figure 10. Photomicrographs from Cherokee No. 22-14 well at 5864.1 feet. A - This sample comes from a rather tight limestone than has no visible matrix porosity under transmitted lighting (see photomicrograph below). However, under fluorescence microscopy, there is some red fluorescence from spike epoxy that has been impregnated into matrix pore spaces. Therefore, the scattered red spots in this image show the presence of some porosity. The abundant bright-yellow specks across the image are probably the result of live-oil staining throughout this relatively low-porosity sample. Note the dull-green areas which show some relict preservation of the peloids (for example E-3, F-4, and L-8) that were the principal constituent of this carbonate sediment. B - The same field of view as above is shown under plane light at the same magnification. There is no visible matrix porosity in this image (that is, no blue colors) despite the appearance in some areas of fluorescing epoxy-filled pores in the image above. In addition, the peloids that can be seen in the fluorescence view are very difficult to make out in this transmitted-light view.

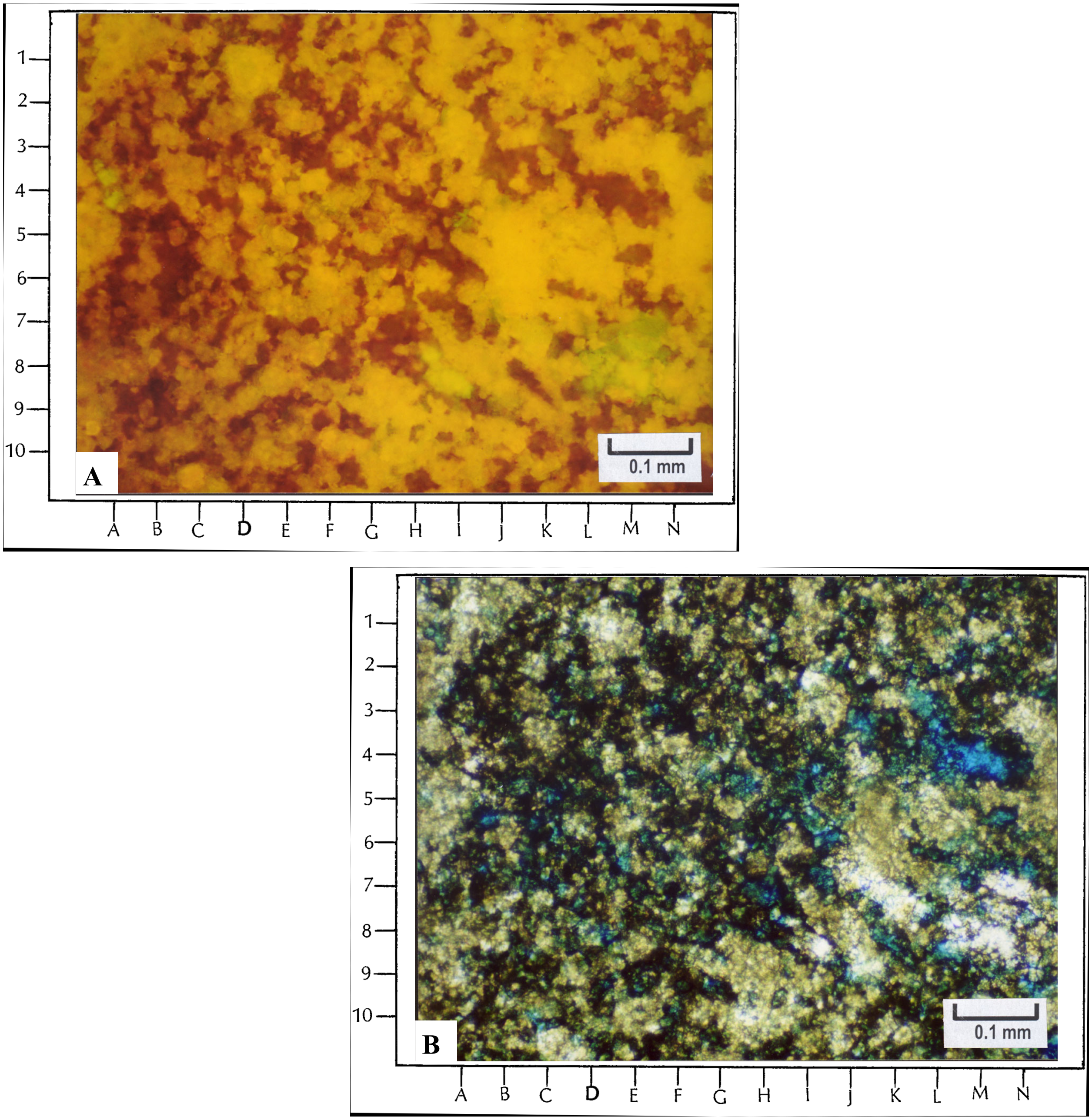


Figure 11. Photomicrographs from Cherokee No. 33-14 well at 5773.9 feet. A - This representative epifluorescence photomicrograph nicely shows the distribution and shapes of open pores which appear here in the shades of red. Many of these pores are somewhat elongate and are moldic in origin. Most result from the dissolution of small, phylloid-algal plates and possibly other fossil skeletons. Many of these dissolution pores appear to be well connected. The yellow areas are oil-stained carbonates which are mostly composed of limestone here. The light green areas (for example B-3.5 and M-7) are patches of anhydrite cementation. B - The same field of view as above is shown under plane light at the same magnification. Note that the areas of blue-dye colored epoxy are not abundant or as distinct as the areas in red within the fluorescence photomicrograph above. Without the aid of the fluorescence view, the amount of visible open pore space would be underestimated in the plane-light image.

5801.3 feet: This sample also displays significant heterogeneity in porosity distribution. Blue-light epifluorescence made it possible to image the quantity and quality of microporosity throughout the sample (figure 9). "Micro-sucrosic" dolomite appears to dominate this sample with an excellent micro-intercrystalline pore structure that could not be resolved without fluorescence microscopy. Low-amplitude stylolites act as significant vertical permeability barriers between different layers of well-developed matrix microporosity. Replacement of the matrix rock by dolomite and the development of micro-intercrystalline porosity appears to be greatly reduced in areas immediately adjoining the stylolites.

5864.1 feet: Epifluorescence of a very dense limestone containing abundant, closely spaced, wispy, stylolite seams reveals some very interesting textural and porosity information (figure 10). Under plane transmitted light, this sample appears to be a dense lime mudstone, whereas fluorescence examination clearly shows distinct grain-supported peloids. More importantly, epifluorescence reveals small compartments of good porosity separated from much tighter rocks by subhorizontal stylolitic seams. Hence, some of the stylolites and wispy seams with concentrations of insoluble residues act as barriers to vertical fluid flow between the porous compartments. Epifluorescence also suggests that the origin of the porosity may be related to dissolution of the peloidal limestone matrix after the formation of the stylolites.

Cherokee Federal No. 33-14 Well: 5773.9 feet

This sample of slightly dolomitic limestone shows high amounts of microporosity and solution-enlarged pores that are difficult to image under plane-polarized lighting. Blue-light epifluorescence images nicely show the open pores and their shapes despite the presences of variable amounts of black bitumen lining pore walls (figure 11). In addition, epifluorescence nicely shows remnants of fossils and non-skeletal grains (peloids and possibly ooids), as well as excellent examples of zoned, replacement, dolomite crystals.

TECHNOLOGY TRANSFER

The UGS is the Principal Investigator and prime contractor for three petroleum-research projects, including two in the Paradox Basin. These projects are designed to improve recovery, development, and exploration of the nation's oil and gas resources through use of better, more efficient technologies. The projects involve detailed geologic and engineering characterization of several complex heterogeneous reservoirs. The Class II Oil Revisit project, described in this report, includes a practical oil-field demonstration of selected technologies in the Paradox Basin. The second Paradox Basin project will evaluate exploration methods and map regional facies trends for independents interested in the Mississippian Leadville Limestone play. The third project is part of the DOE Preferred Upstream Management Practices (PUMP II) program. That project, titled *Major Oil Plays in Utah and Vicinity*, will describe and delineate oil plays in the Utah/Wyoming thrust belt, Uinta Basin, and Paradox Basin. The DOE and multidisciplinary teams from petroleum companies, petroleum service companies, universities, private consultants, and state agencies are assisting with the three projects.

The UGS intends to release selected products of the Class II Oil Revisit Paradox Basin project in a series of formal publications. These publications may include data, as well as the results and interpretations. Syntheses and highlights will be submitted to refereed journals, as appropriate, such as the *American Association of Petroleum Geologists (AAPG) Bulletin* and *Journal of Petroleum Technology*, and to trade publications such as the *Oil and Gas Journal*. This information will also be released through the UGS periodical *Survey Notes* and be posted on the UGS Paradox Basin project Web page.

The Technical Advisory Board advises the technical team on the direction of study, reviews technical progress, recommends changes and additions to the study, and provides data. The Technical Advisory Board is composed of 13 field operators from the Paradox Basin (Seeley Oil Co., Legacy Energy Corp., Pioneer Oil & Gas, Hallwood Petroleum Inc., Dolar Oil Properties, Cochrane Resources Inc., Wexpro Co., Samedan Oil Corp., Questar Exploration, Tom Brown Inc., PetroCorp Inc., Stone Energy LLC., and Sinclair Oil Corp.). This board ensures direct communication of the study methods and results to the Paradox Basin operators. The Stake Holders Board is composed of groups that have a financial interest in the study area including representatives from Utah and Colorado state governments (Utah School and Institutional Trust Lands Administration; Utah Division of Oil, Gas and Mining; and Colorado Oil and Gas Conservation Commission), Federal Government (U.S. Bureau of Land Management and U.S. Bureau of Indian Affairs), and the Ute Mountain Ute Indian Tribe. The members of the Technical Advisory and Stake Holders Boards receive all semi-annual technical reports and copies of all publications, and other material resulting from the study.

The project technical team met with Technical Advisory and Stake Holders Boards in Denver, Colorado, on August 12, 2004. Project activities, results, and recommendations for horizontal drilling were presented. In addition, the UGS offered members of the Technical Advisory Board the first opportunity to receive 35 percent (up to $200,000), for the cost to drill a lateral(s) from an existing vertical well(s) or new horizontal well(s) in the Ismay and Desert Creek zones of Paradox Basin fields in Utah or Colorado. This offer was the result of decisions by the operators of the Cherokee and Bug fields not to conduct horizontal drilling activities at this time. Parties interested in conducting horizontal drilling in fields they operate were told to provide the following information to the UGS by November 30, 2004: (1) a geologic overview of the field, (2) targeted zone(s), (3) depth, length, and directions of proposed horizontal wellbore(s), (4) drilling rationale, (5) drilling cost summary (AFE), and (6) drilling timetable.

Project materials, plans, objectives, and results were displayed at the UGS booth during the AAPG Annual Convention, April 18-24, 2004, in Dallas, Texas, and at the AAPG Rocky Mountain Section Meeting/Rocky Mountain Natural Gas Strategy Conference and Investment Forum (hosted by the Colorado Oil & Gas Association), August 9-11, 2004, in Denver, Colorado. Four UGS scientists staffed the display booth at these events. Project displays will be included as part of the UGS booth at professional meetings throughout the duration of the project.

Utah Geological Survey *Survey Notes* and Web Site

The purpose of *Survey Notes* is to provide non-technical information on contemporary geologic topics, issues, events, and ongoing UGS projects to Utah's geologic community, educators, state and local officials and other decision makers, and the public. *Survey Notes* is published three times yearly. Single copies are distributed free of charge and reproduction (with recognition of source) is encouraged. The UGS maintains a database that includes those companies or individuals (more than 300 as of October 2004) specifically interested in the Paradox Basin project or other DOE-sponsored UGS projects. They receive *Survey Notes* and notification of project publications and workshops.

The UGS maintains a Web site, http://geology.utah.gov. The UGS site includes a page under the heading *Oil, Gas, Coal, & CO_2*, which describes the UGS/DOE cooperative studies past and present (Paradox Basin, Ferron Sandstone, Bluebell field, Green River Formation, PUMP II), and has a link to the DOE Web site. Each UGS/DOE cooperative study also has its own separate page on the UGS Web site. The Paradox Basin project page http://geology.utah.gov/emp/Paradox2/index.htm contains (1) a project location map, (2) a description of the project, (3) a list of project participants and their postal addresses and phone numbers, (4) a reference list of all publications that are a direct result of the project, (5) semi-annual technical progress reports, and (6) project technical poster displays.

Non-Technical Presentation

The following non-technical presentation was made to the Grand County Council, members of the press, and general public, during the first six months of the fifth project year as part of the technology transfer activities:

> "Heterogeneous Shallow-Shelf Carbonate Buildups in the Blanding Sub-Basin of the Paradox Basin, Utah and Colorado: Targets for Increased Oil Production & Reserves Using Horizontal Drilling Techniques" by Thomas C. Chidsey, Jr., Moab, Utah, May 4, 2004. The petroleum geology of the Paradox Basin and an overview of project goals, activities, and results were part of the presentation.

Project Publication

Chidsey, T.C., Jr., Wakefield, Sharon, and Eby, D.E., 2004, Heterogeneous shallow-shelf carbonate buildups in the Paradox Basin, Utah and Colorado: targets for increased oil production and reserves using horizontal drilling techniques – semi-annual technical progress report for the period October 6, 2003 to April 5, 2004: U.S. Department of Energy, DOE/BC15128-8, 46 p.

CONCLUSIONS

1. Epifluorescence petrography makes it possible to clearly identify grain types and shapes, within both limestone and dolomite reservoir intervals in upper Ismay zone thin sections from cores examined in this study. In particular, identification of peloids, skeletal grain types, and coated grains are easy to see in rocks where these grains have been poorly preserved, partially leached, or completely dolomitized.

2. Depositional textures that are frequently occult or poorly preserved can often be clearly distinguished using blue-light epifluorescence microscopy. In many of the microporous limestones and finely crystalline dolomites of the upper Ismay reservoir at Cherokee field,

the differences between muddy and calcarenitic fabrics can only be clearly appreciated with fluorescence lighting.

3. Epifluorescence petrography clearly and rapidly images pore spaces that cannot otherwise be seen in standard viewing under transmitted polarized lighting. In addition, the cross-sectional size and shape of pores are easy to determine.

4. Much of the upper Ismay zone porosity is very heterogeneous and poorly connected as viewed under epifluorescence. In particular, microporosity within some of the upper Ismay reservoir section in Cherokee field can be resolved much more clearly than with transmitted polarized lighting. The epifluorescence examination helps in seeing the dissolution origin of most types of the microporosity. Transmitted polarized lighting does not image microporosity in carbonate samples very well, even though blue-dyed epoxy can be impregnated into even very small pores. This porosity does not show up very well because the pores are much smaller than the thickness of the thin section, and hence carbonate crystallites on either side of micropores are seen rather than the pores. In addition, opaque bitumen linings prevent light from passing through some of the pores to the observer. Without the aid of the epifluorescence view, the amount of visible open pore space would be underestimated in the plane-light image.

5. Where dolomitization has occurred, epifluorescence petrography often shows the crystal size, shape, and zonation far better than transmitted plane or polarized lighting. This information is often very useful when considering the origin and timing of dolomitization as well as evaluating the quality of the pore system within the dolomite.

6. Permeability differences within these dolomite and limestone samples are also easy to image because of the differential oil saturations between the tighter areas and the more permeable lithologies. Low-permeability carbonates from this study area show bright yellow fluorescence due to trapped live oil that is retained within tighter parts of the reservoir system. More permeable rocks show red fluorescence due to the epoxy fluorescence where oil has almost completely drained from the better quality portions of the reservoir.

7. Fluorescence of dense, “muddy” limestone and dolomite containing abundant, closely spaced, wispy stylolite seams often reveals some very interesting textural and porosity information. Under plane transmitted light, these types of samples appear to be a dense lime mudstone whereas epifluorescence examination clearly shows distinct grain-supported peloids. More importantly, epifluorescence frequently reveals small compartments of good porosity separated from much tighter rocks by subhorizontal stylolitic seams. Hence, some of the stylolites and wispy seams with concentrations of insoluble residues act as barriers to vertical fluid flow between the porous compartments. Epifluorescence also suggests that the origin of the porosity may be related to dissolution of the peloidal limestone matrix after the formation of the stylolites.

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Core and petrophysical data were provided by Burlington Resources and Seeley Oil Company. Jim Parker of the Utah Geological Survey (UGS) drafted figures. The report was reviewed by David Tabet and Mike Hylland of the UGS. Cheryl Gustin, UGS, formatted the manuscript for publication.

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